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SMOKE PRODUCED BY BURNING
AIRCRAFT FINISH MATERIALS

by

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for

Federal Aviation Agency
Washington, D. C.

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NATIONAL BUREAU OF STANDARDS

SMOKE PRODUCED BY BURNING AIRCRAFT
FINISH MATERIALS

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ABSTRACT

Smoke measurements and an indication of the concentrations of some toxic decomposition products resulting from open flaming and smouldering combustion of 15 aircraft finish materials are reported. Charts and tables are included to facilitate estimating approximate smoke and gas concentrations which might exist in aircraft during an assumed fire exposure.

SMOKE PRODUCED BY BURNING AIRCRAFT FINISH MATERIALS

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1. Materials

A total of 15 materials were hand-delivered by FAA personnel on 9 and 17 February. All materials were stored in a specimen conditioning laboratory at 73°F and 50 percent relative humidity for at least one week prior to test. The materials are listed in Table I.

2. Test Method

Smoke measurements and indications of toxic gas concentrations were made in an enclosed smoke chamber similar to that described in NBS Report No. 8947. Tests were performed under both flaming and non-flaming (smoldering) exposure. The former test involved irradiating the normally exposed surface of the specimen (2-9/16 in. square) with 2.5 watts/cm² and the application of a small pilot flame to induce open flaming. The latter test involved the same radiant exposure without the pilot flame. The smoke level was determined by measuring the progressive attenuation of a light beam passed through the smoke aerosol. Indications of the toxic gas concentration were obtained by drawing a sample of the gas mixture in the test chamber through commercial colorimetric gas detector tubes and reporting results on the basis of the manufacturers calibrations for the selected gases. In some instances an attempt was made to extend the range of these indicators by drawing less than the recommended gas volume through them and reporting results on the assumption of linearity of indicated concentrations with sample volume used.

3. Smoke Measurement

Smoke is reported in terms of a specimen property, specific optical density, a dimensionless attenuation coefficient which relates the quantity of smoke accumulated from a specimen of given thickness, in terms of photometric obscuration.

Optical density is defined as $D = \log_{10} \frac{100}{T}$ (where T = percent light transmission), and is the single most characteristic measure of the obscuring quality of a smoke. If the smoke is produced from a surface of area A and collected in a closed chamber of volume V, the optical density of the generated smoke should be directly proportional to A and inversely proportional to V. Optical density is also proportional to the optical path length L, so that it is appropriate to write

$$D = D_s \frac{AL}{V}$$

D_s is termed the specific optical density, and represents the optical density measured over unit path length within a chamber of unit volume produced from a specimen of unit surface area. Thus,

$$D_s = D \frac{V}{AL} = \frac{V}{AL} \log_{10} \frac{100}{T}$$

For the test chamber, $V = 18 \text{ ft}^3$, $A = 0.0456 \text{ ft}^2$, and $L = 3 \text{ ft}$. Ideally, the change in D_s with time during the smoke accumulation process will depend only upon the thickness of the specimen, its chemical and physical properties, and the exposure conditions. However, there are definite limitations to the use of specific optical density for extrapolation and comparison with other box volumes, specimen areas and photometric systems, and for extension to human visibility. The degree to which such extensions are valid depend upon a number of major assumptions: the smoke generated is uniformly distributed, and is independent of the amount of excess air available and of any specimen edge effects; coagulation and deposition of smoke is similar regardless of the specimen size, or the size and shape of the chamber; for any given smoke the optical density is linearly related to concentration; and human and photometric vision through light-scattering smoke aerosols, expressed in terms of optical density, are similar.

4. Toxic Gas Measurement

Several times during each smoke test, a measured volume of gas was drawn through one of several commercial gas detector tubes, using a small syringe or bellows pump. Concentration was indicated by a color change for carbon monoxide (M-S-A Carbon Monoxide Tester), and by the length of color stain along pre-calibrated detector tubes for all other gases (Dräger Multi-Gas Detector). The gas detector tube was inserted into the smoke chamber from the top, and was situated approximately 20 inches above the specimen.

Indicator tubes were used to search for CO , HCl , HCN , NO_2 , Cl_2 , NH_3 and COCl_2 . Information regarding the measuring range, interfering reactions, reuse, and the effects of temperature and relative humidity were provided by the detector tube manufacturer. The upper and lower limits of the measuring ranges for these tubes and some references to the toxic hazard limits of these gases are summarized in Table II. The toxic limits, which are included only as background information, are not well defined, and will be discussed later.

No verification has been made by this laboratory of the manufacturers' claims for the accuracy of the indicators. Although not recommended, a rough estimation was made of HCl concentration above the measuring range using a smaller volume than that prescribed and multiplying the concentration accordingly.



5. Test Results

The test results given in Table I are based on the average of duplicate tests (with few exceptions). Duplicate tests were fairly reproducible in terms of both smoke buildup and indicated gas concentration.

The smoke buildup curves for a typical flaming and a typical smoldering test on each material are shown in Figures 1 through 15. In Table I are listed the specific optical density at a time of 2 minutes, and the peak specific optical density. For Materials 10 and 11 under flaming exposure, peak specific optical density values were not directly measurable since the very heavy smoke concentrations exceeded the measuring capability of the system.

Except for CO, HCl and HCN, indicated gas concentration levels were generally below the M.A.C. values, so that interest was mainly confined to these three gases. Although only a limited number of gas measurements could be taken during each test, the peak indication appeared to occur at approximately the same time as the peak smoke level. It was noted, however, that the indicated HCl concentration dropped off rapidly after reaching a peak, whereas the CO and HCN indications tended to maintain their peak indications for much longer periods.

6. Discussion

Limitations were previously noted to the use of specific optical density for extrapolation to other enclosure volumes and surface areas. Within these limitations, the relationship between the measured value of D_s and the geometrical factor $\frac{V}{LA}$ for various values of light transmission (or optical density) is shown in Figure 16. The optical density level through which a lighted exit sign may be seen can vary over wide limits depending on the general illumination level, on the contrast threshold and the extent to which the observer's eyes have been dark-adapted, as well as on the irritating nature of the smoke. In Figure 16, five lines are shown for transmission values ranging from 80 to 2.5 percent (optical density 0.1 to 1.6) corresponding to the possible range of visual limits.

If, as an example, it is assumed that a lighted exit sign can be seen when the transmission is down to 40% (optical density 0.4), and an aircraft cabin has a volume of 10,000 ft³ within which smoke is uniformly dispersed, then Table III shows the estimated area A of material which may just begin to limit seeing the exit sign at various distances L for several values of D_s . The choice of a critical specific optical density for each material

can presumably be based on a prescribed time period which is sufficiently long to permit escape or defensive action. In Table I are listed values of D_s at a time of 2 minutes after the start of thermal exposure (flaming or nonflaming), and it may be noted that these varied from 0 to 525 for the 15 materials tested. The peak specific optical density values varied from below 20 to over 530.

It has been assumed that the only smoke-producing material involved was a single layer of the material tested. In the case of the foam seat cushion (Material 15), the specimen thickness was only 1/2 inch, whereas the cushion was about 3 inches thick.

As noted previously, no verification was made by this laboratory of the manufacturers' claims for the accuracy of the colorimetric gas indicator tubes. The use of the recorded values as true concentration values with any high degree of confidence may be limited by a number of factors, including the time and location of sampling, the effects of relative humidity and elevated temperatures, the absorption of gas on the surfaces of the chamber and on smoke particles, interpretation of the color change, and interfering reactions by other gases. The error in reading the color stain length may be up to ± 15 percent in some cases. No correction was made for the temperature of the gas sample, the maximum value of which was approximately 40°C for the smoldering tests and 50 to 85°C for the flaming tests.

Even if the true gas concentrations were known, their use in terms of toxicological limits, such as illustrated in Table II, would still be open to some question. For example, there does not seem to be sufficient information available on the synergistic (combined) effects of several toxic components. It may be noted from the table that reference values of the toxic concentrations lethal within a few minutes can vary from 20 to 400 times the established M.A.C. values for the gases listed. Despite these shortcomings, the colorimetric indicator tubes appear to serve an immediate need, and it is useful to examine and interpret the test results even if only in comparative terms.

In each case (except Material 15), a single layer of the material was subjected to the test exposure. It should be noted that the weight of the specimens (see Table I) varied by a factor of more than 8 and thus gas and smoke concentration would be expected to vary over wide limits.

and the results of the survey are as follows: The first group of results shows that the majority of the respondents are in the age group of 25 to 34 years. The second group of results shows that the majority of the respondents are male. The third group of results shows that the majority of the respondents are single. The fourth group of results shows that the majority of the respondents are employed. The fifth group of results shows that the majority of the respondents are from the urban areas. The sixth group of results shows that the majority of the respondents are from the middle class. The seventh group of results shows that the majority of the respondents are from the Indian subcontinent. The eighth group of results shows that the majority of the respondents are from the United States. The ninth group of results shows that the majority of the respondents are from the United Kingdom. The tenth group of results shows that the majority of the respondents are from the European Union. The eleventh group of results shows that the majority of the respondents are from the Asia-Pacific region. The twelfth group of results shows that the majority of the respondents are from the Latin America and the Caribbean region. The thirteenth group of results shows that the majority of the respondents are from the Middle East and North Africa region. The fourteenth group of results shows that the majority of the respondents are from the Central Asia and the Caucasus region. The fifteenth group of results shows that the majority of the respondents are from the Eastern Europe region. The sixteenth group of results shows that the majority of the respondents are from the Southern Europe region. The seventeenth group of results shows that the majority of the respondents are from the Northern Europe region. The eighteenth group of results shows that the majority of the respondents are from the Western Europe region. The nineteenth group of results shows that the majority of the respondents are from the Central Europe region. The twentieth group of results shows that the majority of the respondents are from the Eastern Europe region.

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From Table I, it may be noted that the CO readings ranged up to 600 ppm. Since a reading of 50 ppm was considered to be the normal background level in the test cabinet, only readings of 100 ppm and above should be considered significant. HCN readings ranging up to 45 ppm were obtained. Here the normal background level was approximately 1 ppm. The background level of HCl appeared to be less than 1 ppm or below the lower detectable limit of the tube. Because HCl gas is very soluble in water, the readings changed more rapidly, and were probably greatly affected by high concentrations of moisture (and smoke). Measurements indicated that the moisture content during these tests was between 10 and 20 mg/liter. The manufacturer reports that for moisture concentrations of 10 mg/liter the HCl colorimetric tube reading is 25 percent low.

High HCl concentrations were indicated for all vinyl (PVC) and modified acrylic-containing materials tested. The readings were generally higher under flaming compared to smoldering exposure conditions, presumably due to the higher temperatures involved. The highest indicated HCl concentrations were developed by Material 12, which was reported to be acrylic-modified PVC (this was also the heaviest material). Materials 9 and 13 also produced high HCl indications. Although the recommended upper measuring range of the HCl tube was only 30 ppm, very rough estimates of higher concentrations were made by using a smaller volume of gas and multiplying the indication accordingly. Therefore, the indicated values are of very limited accuracy.

The highest indicated HCN concentrations were obtained for Materials 2 (modified acrylic) and 7 (acrylic with polyurethane foam). With few exceptions the acrylonitrile-butadiene-styrene (ABS) and wool-containing materials also gave significant indications of HCN. The peak indicated HCN concentrations were very nearly the same under flaming and smoldering exposure.

An approximate relationship between the toxic gas concentration measured in the smoke chamber and the projected concentration within a much larger chamber, such as an aircraft cabin, is given by

$$C_{\text{cabin}} = C_{\text{test}} \left(\frac{V_t}{A_t} \right) \left(\frac{A_c}{V_c} \right)$$

This simply scales concentration (C) in direct proportion to the area A of specimen involved and in inverse proportion to the chamber volume V. As an example, the gas concentration in a 10,000 ft³ cabin is shown in Figure 17 for a series of lines corresponding to surface areas of 10, 100 and 1,000 ft².



7. Summary

Laboratory measurements have been made of the concentrations of combustion-generated smoke and indicated toxic gases for 15 aircraft interior finish materials. Both smoldering and active flaming conditions were considered and it was found that significantly more smoke was produced for several materials in the absence of open flaming.

The smoke concentrations are reported in terms of the optical density, which is the single most characteristic measure of the visual obscuring quality of a smoke. A very wide range of obscuration levels was measured. The general relationship between the measured optical density and the level of smoke through which a lighted exit sign may be seen was discussed, and a method was suggested for extrapolating to other chamber volumes, specimen areas and visual path lengths under ideal conditions.

Toxic gas concentrations, principally CO, HCl and HCN, were indicated using commercial colorimetric gas detector tubes. No verification was made by this laboratory of the manufacturers' claims for the accuracy of the indicators. Considering our limited previous experience with such tubes, and the possible interfering effects of a number of factors, measurements were considered only as "indicated concentrations". Despite these limitations, the colorimetric indicator tubes appear to serve an immediate need, even if the test results are interpreted in comparative terms only. For the materials tested, maximum concentrations of 600 ppm CO, hundreds of ppm HCl, and 45 ppm HCN were indicated. The general relationship between the toxic gas concentrations in the smoke chamber and the projected concentrations within a much larger chamber was presented in graphical form to permit extrapolation to the volume of an airplane cabin and the surface area of material involved.

Table I. Summary of Test Results

Specimen No.	Material Description (as furnished)	Use	Weight oz/yd ²	Thickness in.	Test Exposure	SMOKE		GAS CONCENTRATION			
						Specific Optical Density D _s @ 2 min	D _T (peak)	Maximum Indication-Colorimetric Tube			
								CO	HCl**	ppm	HCN
1	Wool	Curtain	11	0.024	Flaming Non-Flaming	6 36	16 60	20 50	0 0	5 7	
2	Modified Acrylic	Curtain	9.1	0.024	Flaming Non-Flaming	66 43	79 54	80 50	310 180	45 44	
3	Wool/Modified Acrylic	Curtain	14	0.035	Flaming Non-Flaming	38 67	58 96	200 50	60 23	18 14	
4	Wool (Plastic?)	Upholstery	13	0.033	Flaming Non-Flaming	4 2	16 6	70 50	1 0	2 1	
5	Vinyl	Fabric	22	0.026	Flaming Non-Flaming	188 34	198 261	350 250	300 320	1 1	
6	Expanded Vinyl	Fabric	26	0.035	Flaming Non-Flaming	200 30	202 266	300 200	640 450	1 1	
7	Acrylic/Polyurethane Foam	Carpet	62	0.32	Flaming Non-Flaming	335 65	449 367	300 80	300 250	30 45	
8	Polypropylene/Polyethylene	Carpet	36	0.18	Flaming Non-Flaming	31 10	110 456	250 400	1 1	1 2	
9	ABS/(Synthetic Rubber?)	Sheet Mat'l	46	0.045	Flaming Non-Flaming	340 91	389 276	50 70	480 420	14 14	
10	ABS	Sheet Mat'l	36	0.046	Flaming Non-Flaming	525 5	>530 71	0 50	0 0	10 8	
11	ABS	Sheet Mat'l	60	0.076	Flaming Non-Flaming	500 6	>530 167	60 80	0 0	13 13	
12	PVC/Acrylic	Sheet Mat'l	77	0.080	Flaming Non-Flaming	63 3	246 120	600	1000 >2000	1 1	
13	ABS (Vinyl?)/Polyester	Sheet Mat'l	27	0.030	Flaming Non-Flaming	223 0	289 55	50	800 600	3 2	
14	Vinyl/Polyester	Sheet Mat'l	20	0.020	Flaming Non-Flaming	132 11	134 20	300	660 550	1 1	
15	Polyurethane Foam	Cushion	Density 1.7 pcf	.50	Flaming Non-Flaming	16 58	20 156	100 100	0 0	2 2	

* Multiply by 6.6 in.² to obtain weight, in grams, of specimen area exposed

** Indications of HCl concentrations greater than 30 ppm estimated by dilution

Table II. Measuring Range of Colorimetric Indicator Tubes and Toxicological Data for Selected Gases

Indicator Tube Data		Gas						
		CO	HCl	HCN	NO ₂	NH ₃	Cl ₂	COCl ₂
Measuring Range, Lower	ppm	10	2	2	0.5	25	0.2	0.25
		1000	30	150	10	700	30	75
Upper	ppm							
Recommended Upper Temp.								
Limit (tube and test gas)	°C			30	40	40	50	35
<u>Toxicological Data</u>								
M.A.C. ^{a/}	ppm	100	5	10	5	100	1	0.5
Irritation on Brief Exposure ^{b/}	ppm	-	35		75	1500	30	5
Immediate Danger to Life ^{b/} (2 to 5 min)	ppm	10,000	1000-2000	200-300	200	>2000	100	50

^{a/} Maximum average atmospheric concentration for 8-hr day adopted by American Conference of Govt Industrial Hygienists, 1963.

^{b/} Draeger Information Sheets (includes toxicological references).

Table III

Critical (Projected) Surface Area of Material
Burned in 10,000 ft³ Volume

Specific Optical Density D_s	V/LA (for OD = .4)	Light Distance L	Specimen Area A
10	25	3 ft	133 sq ft
10	25	10	40
10	25	30	13.3
10	25	100	4
50	125	3	26.7
50	125	10	8
50	125	30	2.67
50	125	100	0.8
100	250	3	13.3
100	250	10	4.0
100	250	30	13.3
100	250	100	0.4

SMOKE PRODUCTION

NO. 1

TRANSMISSION, PERCENT

SPECIFIC OPTICAL DENSITY, D_s

NON-FLAMING
 $D_T = 64$

FLAMING
 $D_T = 20$

TIME, MINUTES

100

50

20

10

5

2

1

0.1

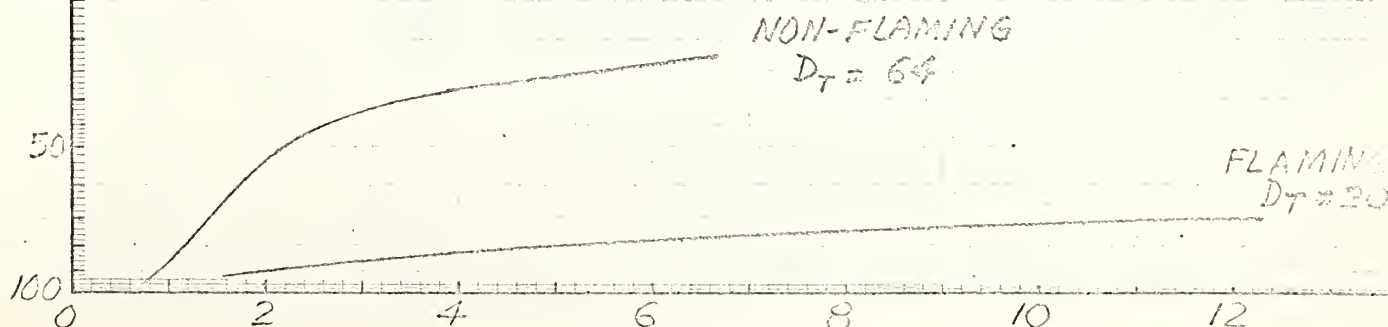
100

200

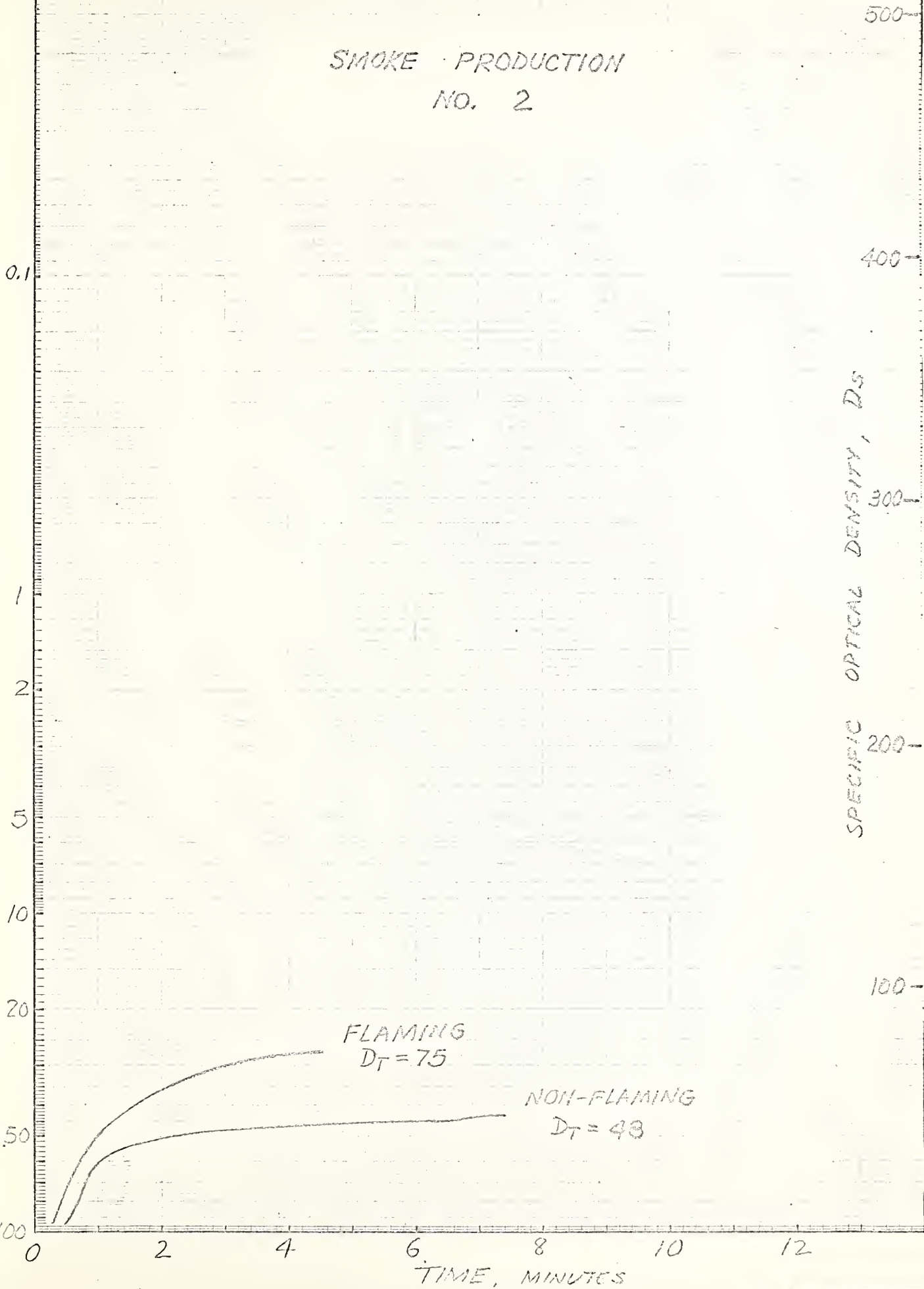
300

400

500



SMOKE PRODUCTION
No. 2



SMOKE PRODUCTION
NO. 3

0.1

400

SPECIFIC OPTICAL DENSITY, D_S

300

200

NON-FLAMING
 $D_T = 89$

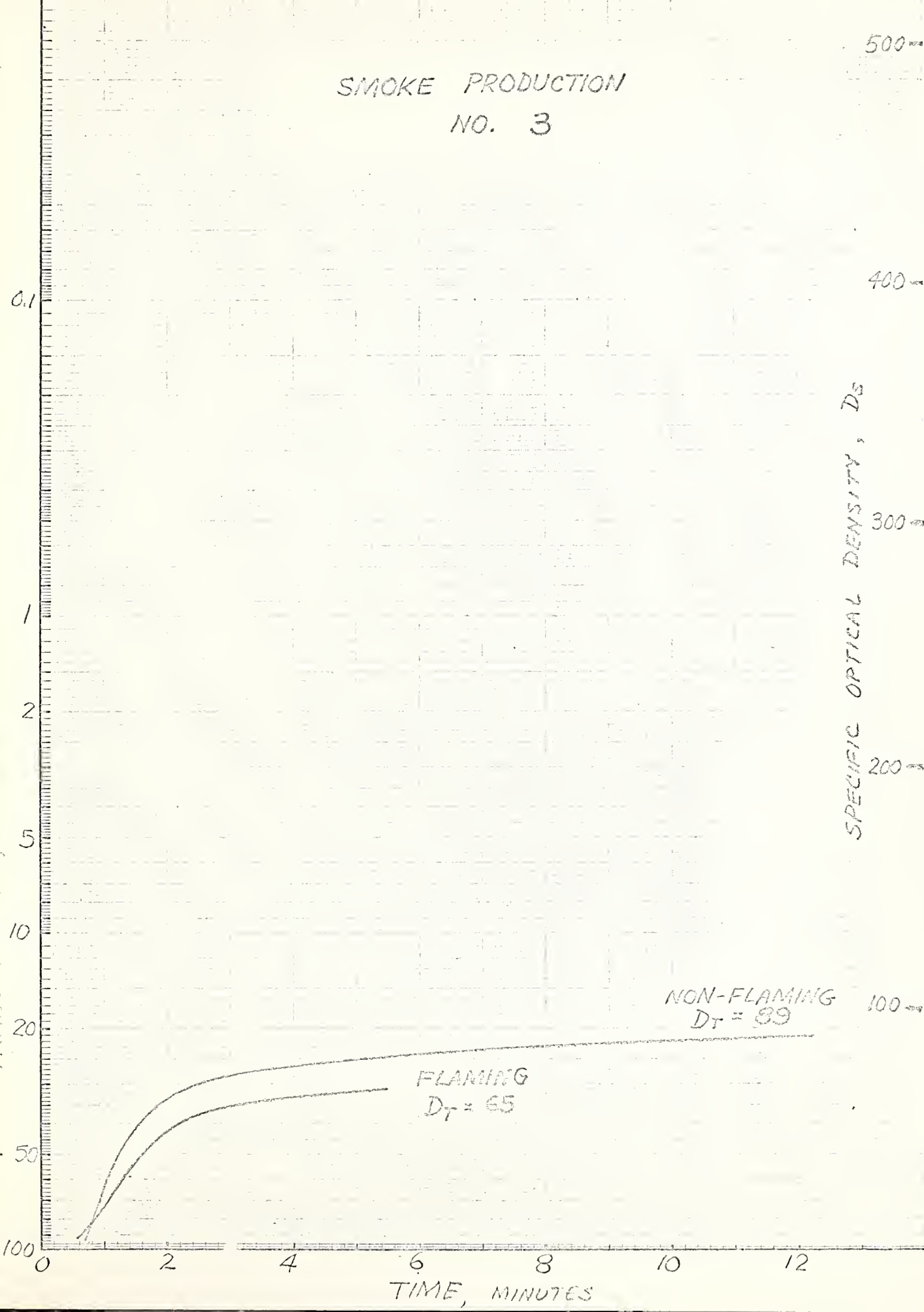
100

FLAMING
 $D_T = 65$

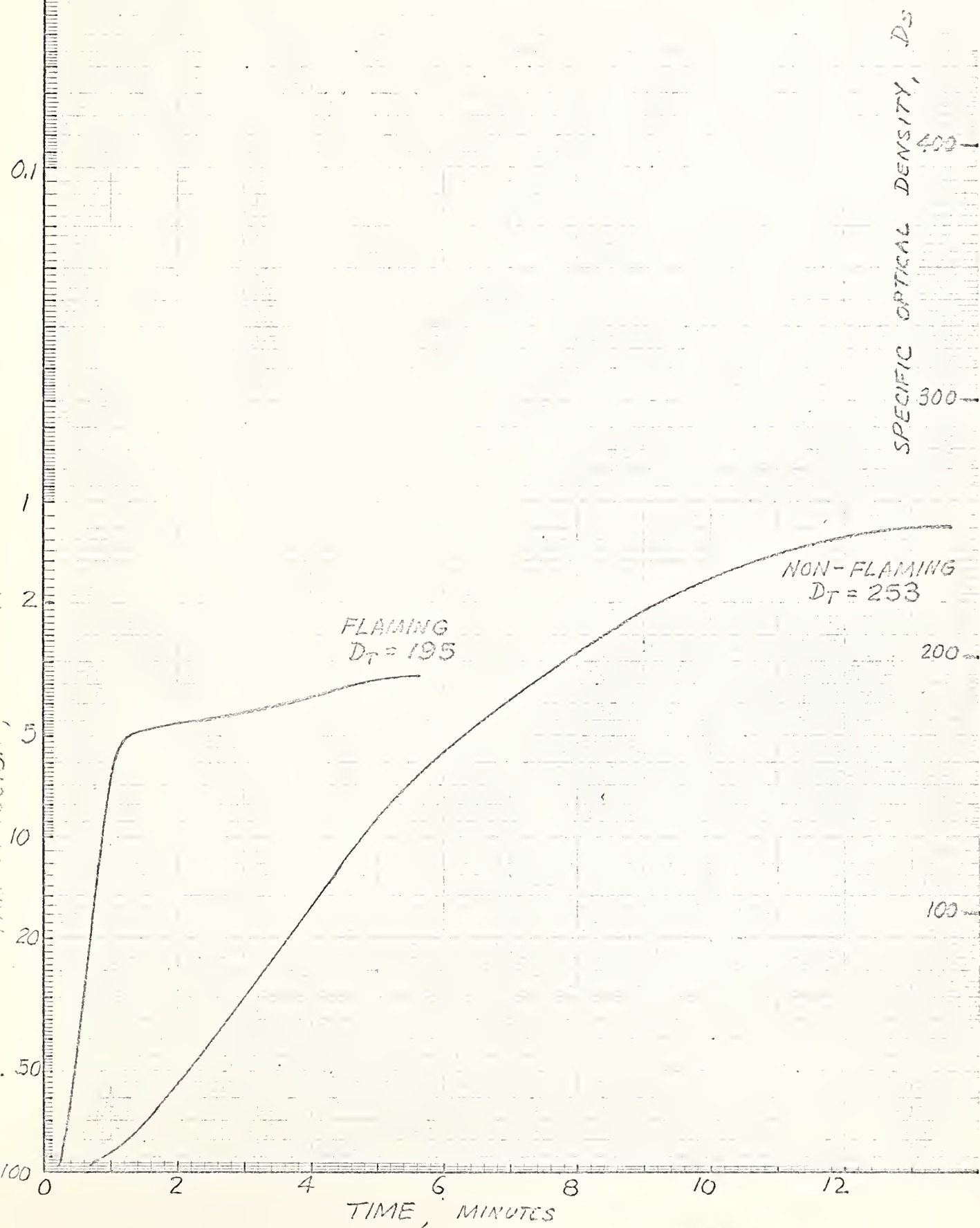
50

100

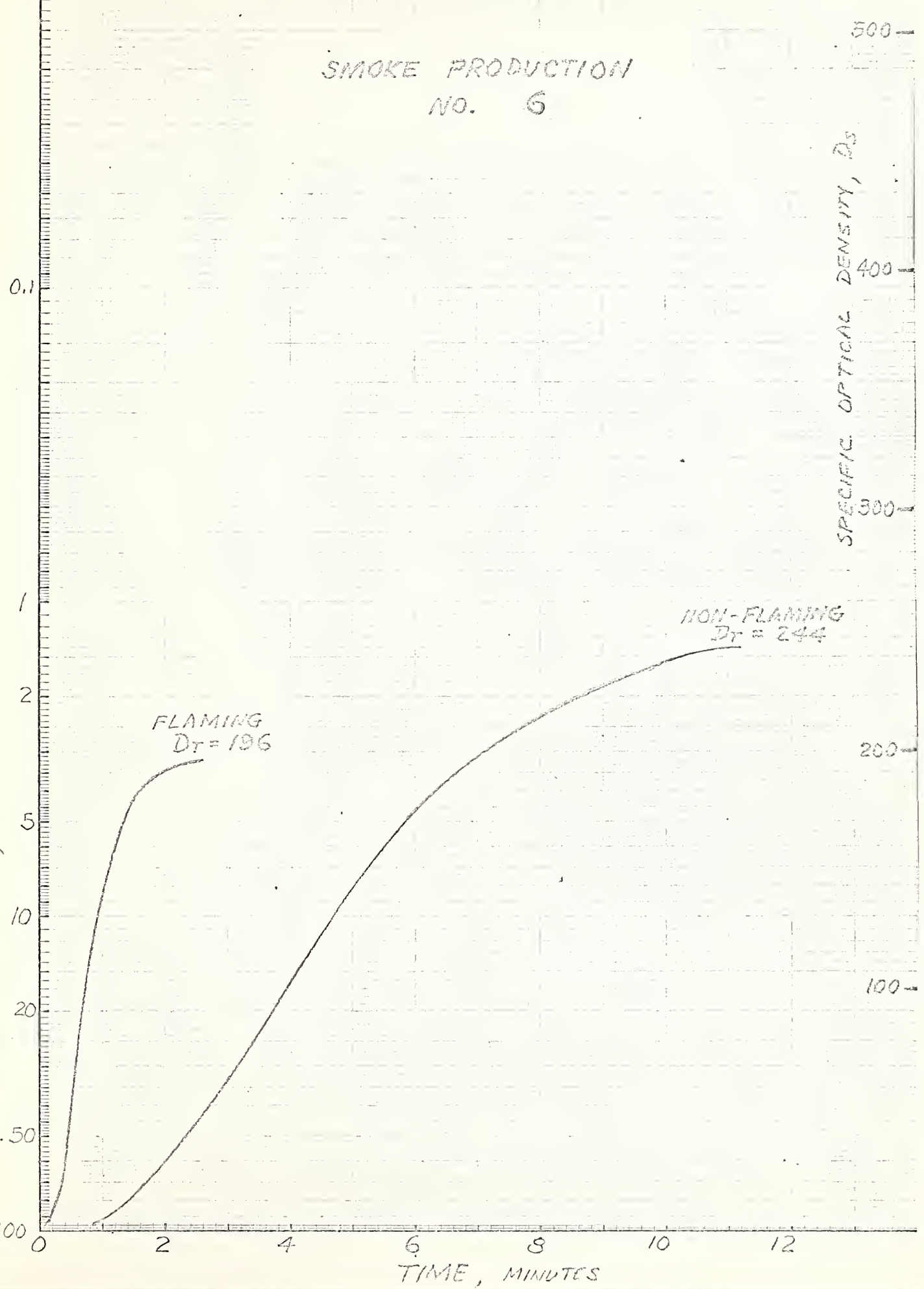
TIME, MINUTES



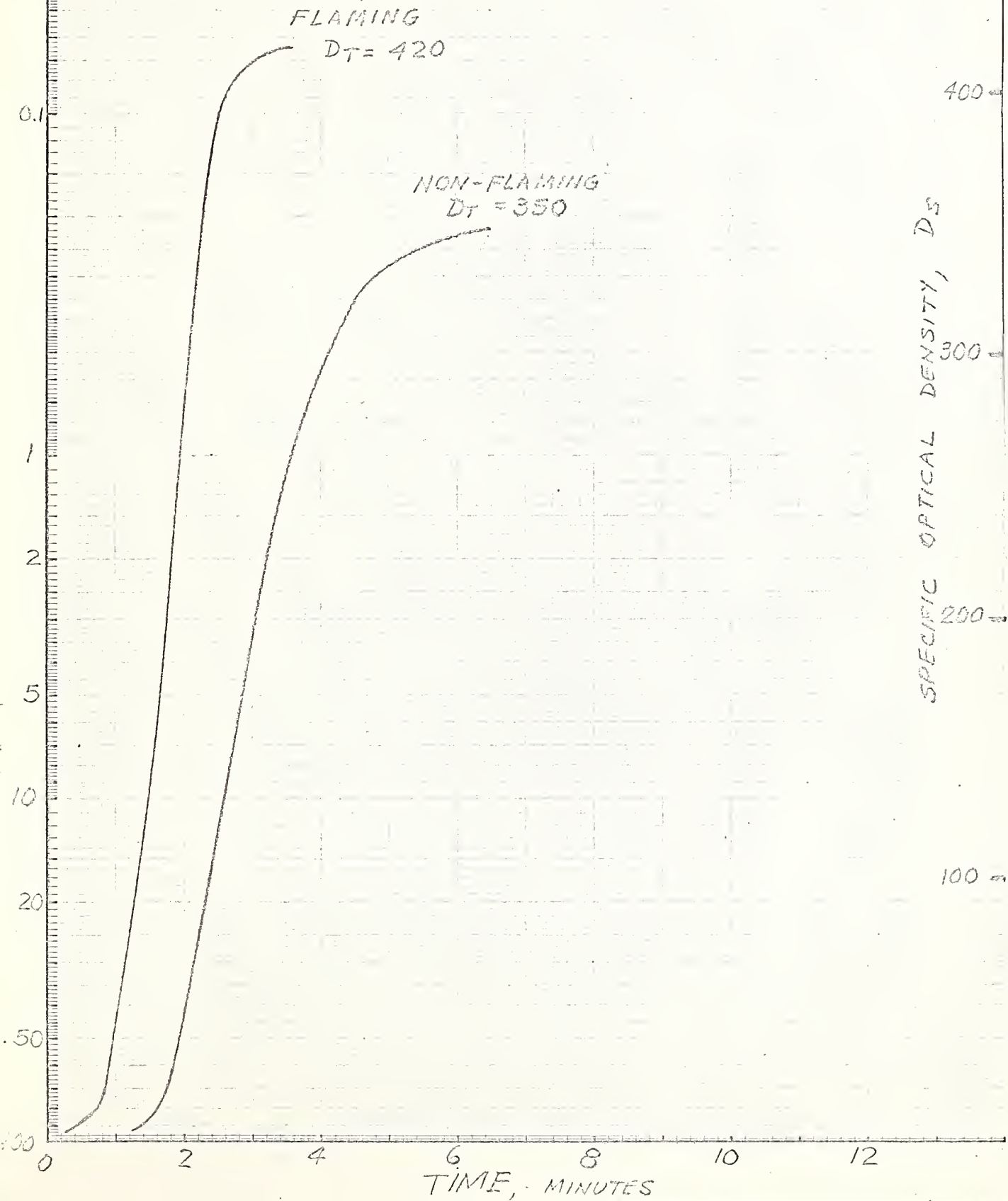
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SMOKE PRODUCTION
NO. 6



SMOKE PRODUCTION NO. 7

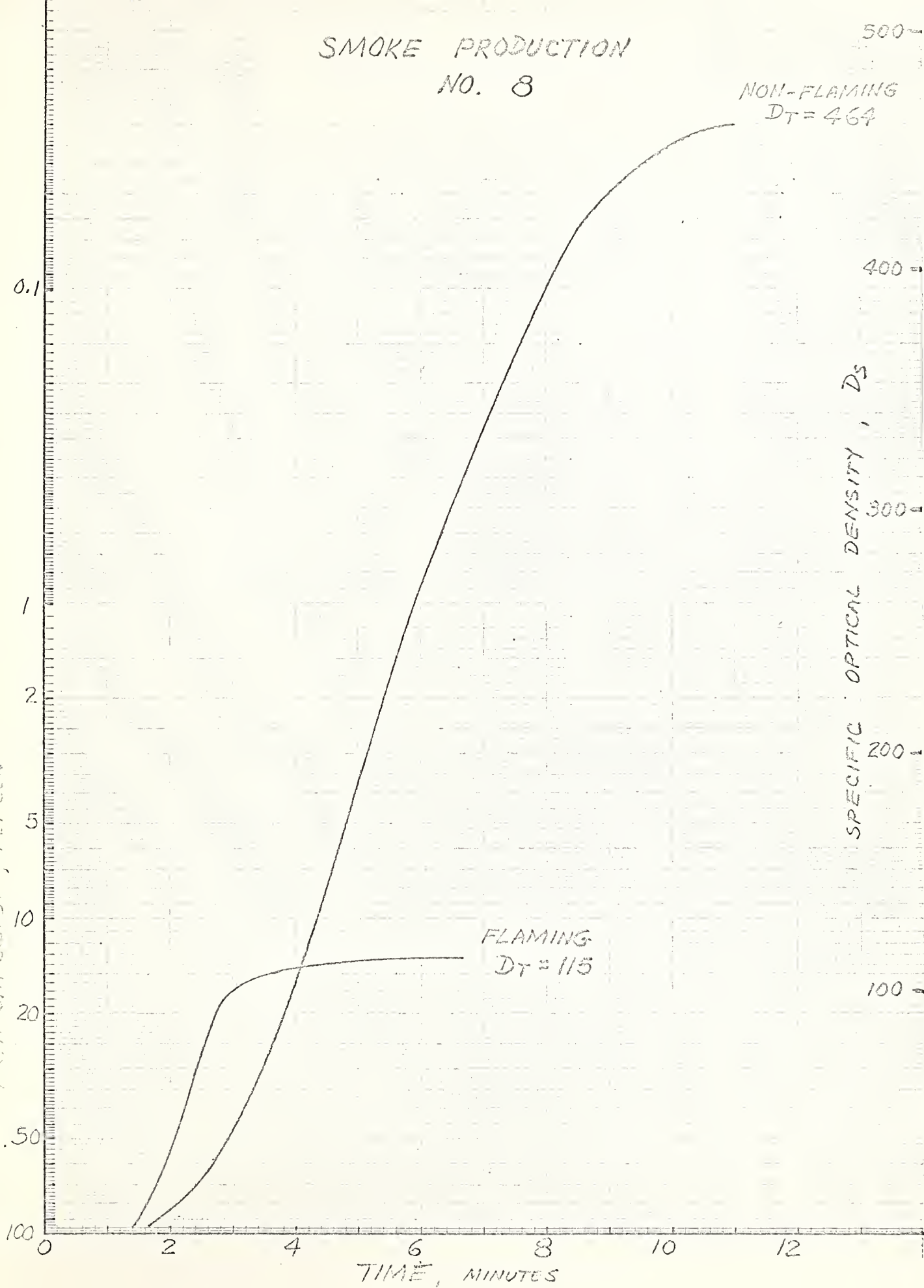


SMOKE PRODUCTION NO. 8

NON-FLAMING
 $D_T = 464$

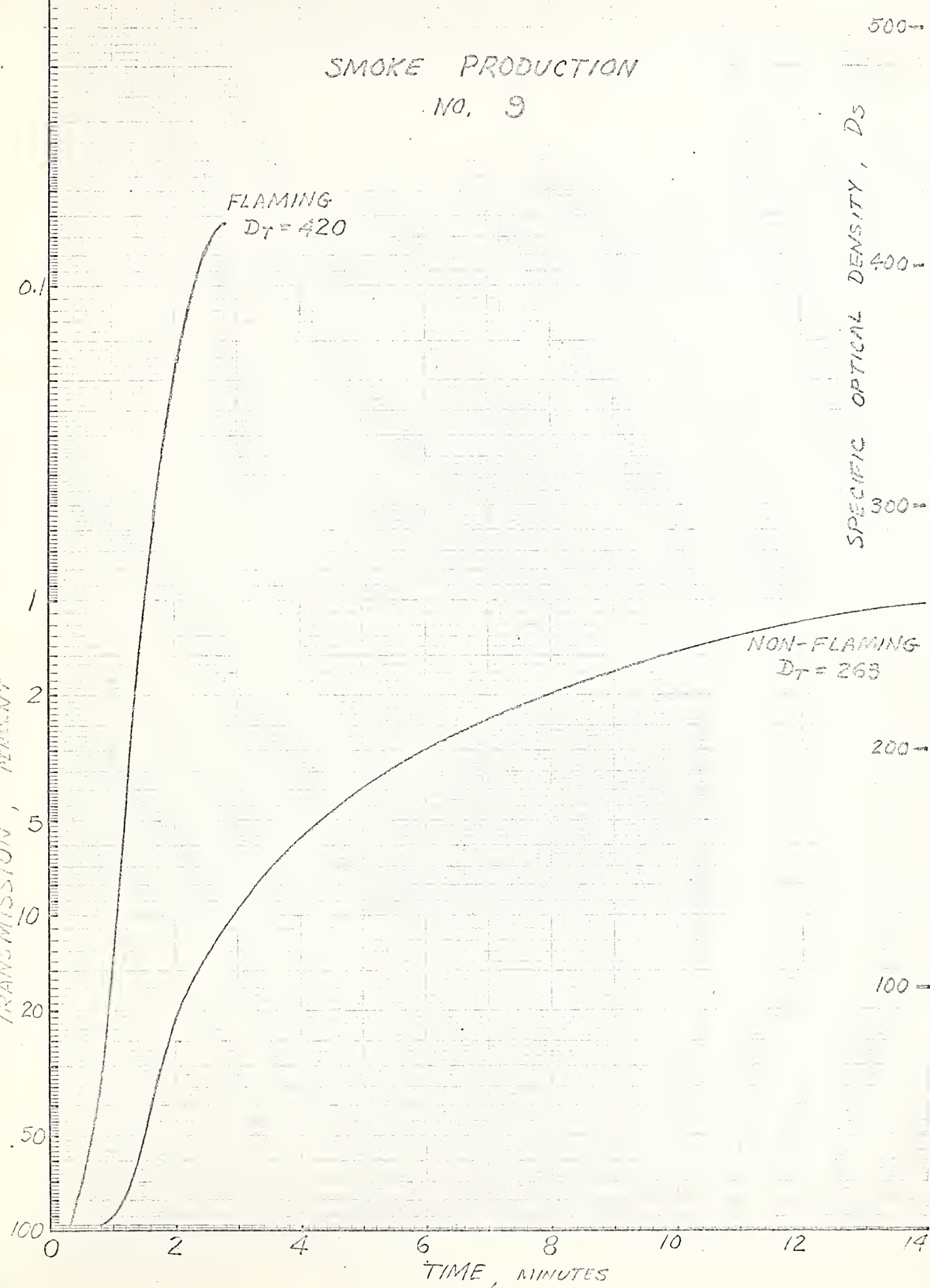
SPECIFIC OPTICAL DENSITY, D_s

FLAMING
 $D_T = 115$



SMOKE PRODUCTION

NO. 9



FLAMING
 $D_T > 530$

500

SMOKE PRODUCTION NO. 10

100

0.1

SPECIFIC OPTICAL DENSITY, D_s

300

200

100

NON-FLAMING
 $D_T = 69$

TIME, MINUTES

TRANSMISSION, PERCENT

100

0

2

4

6

8

10

12

50

10

5

2

1

FLAMING
 $D_T > 530$

500

SMOKE PRODUCTION NO. 11

400

SPECIFIC OPTICAL DENSITY

300

200

NON-FLAMING
 $D_T \approx 143$

100

TRANSMISSION, PERCENT

0.1

1

10

100

2

4

6

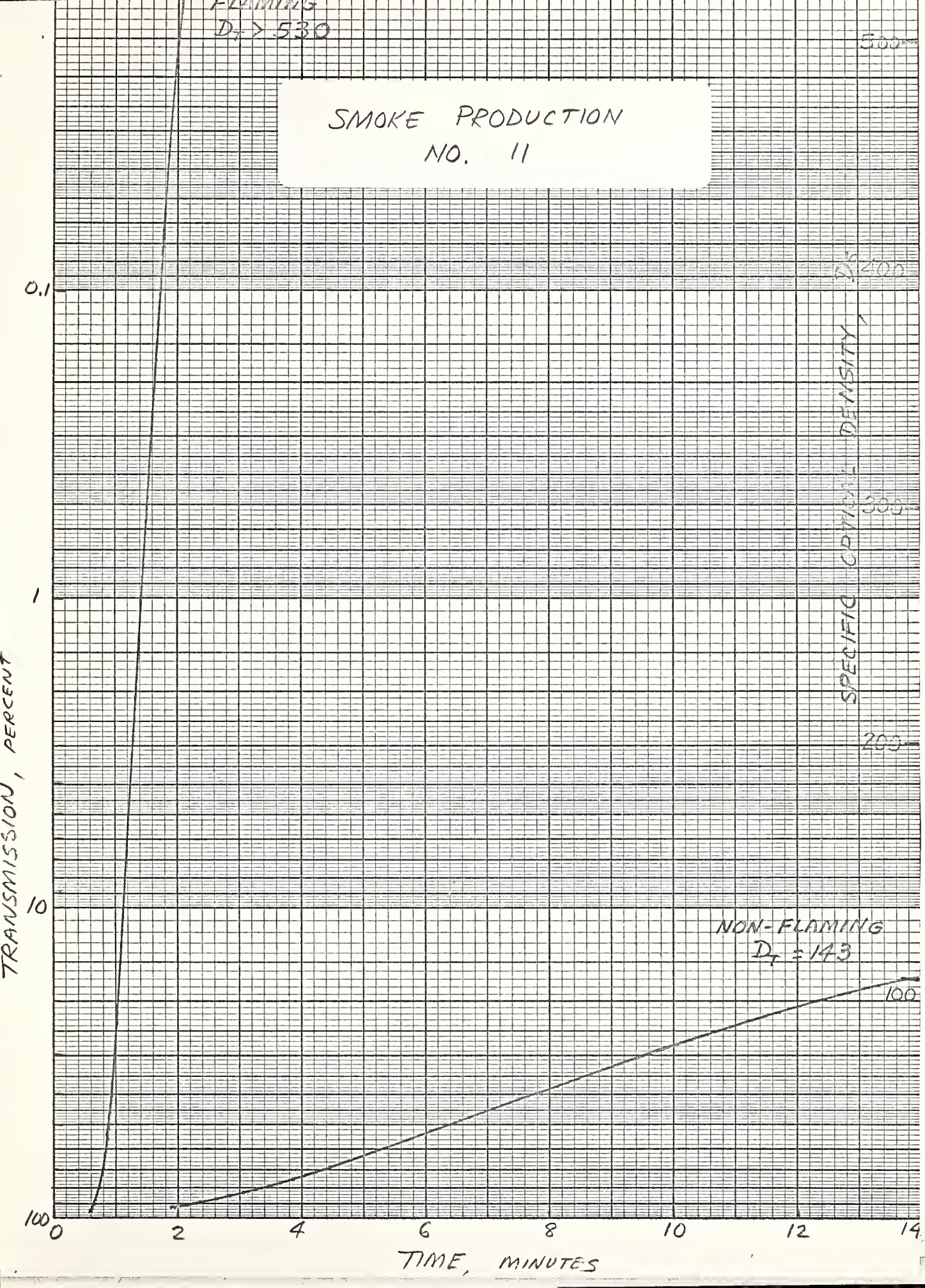
8

10

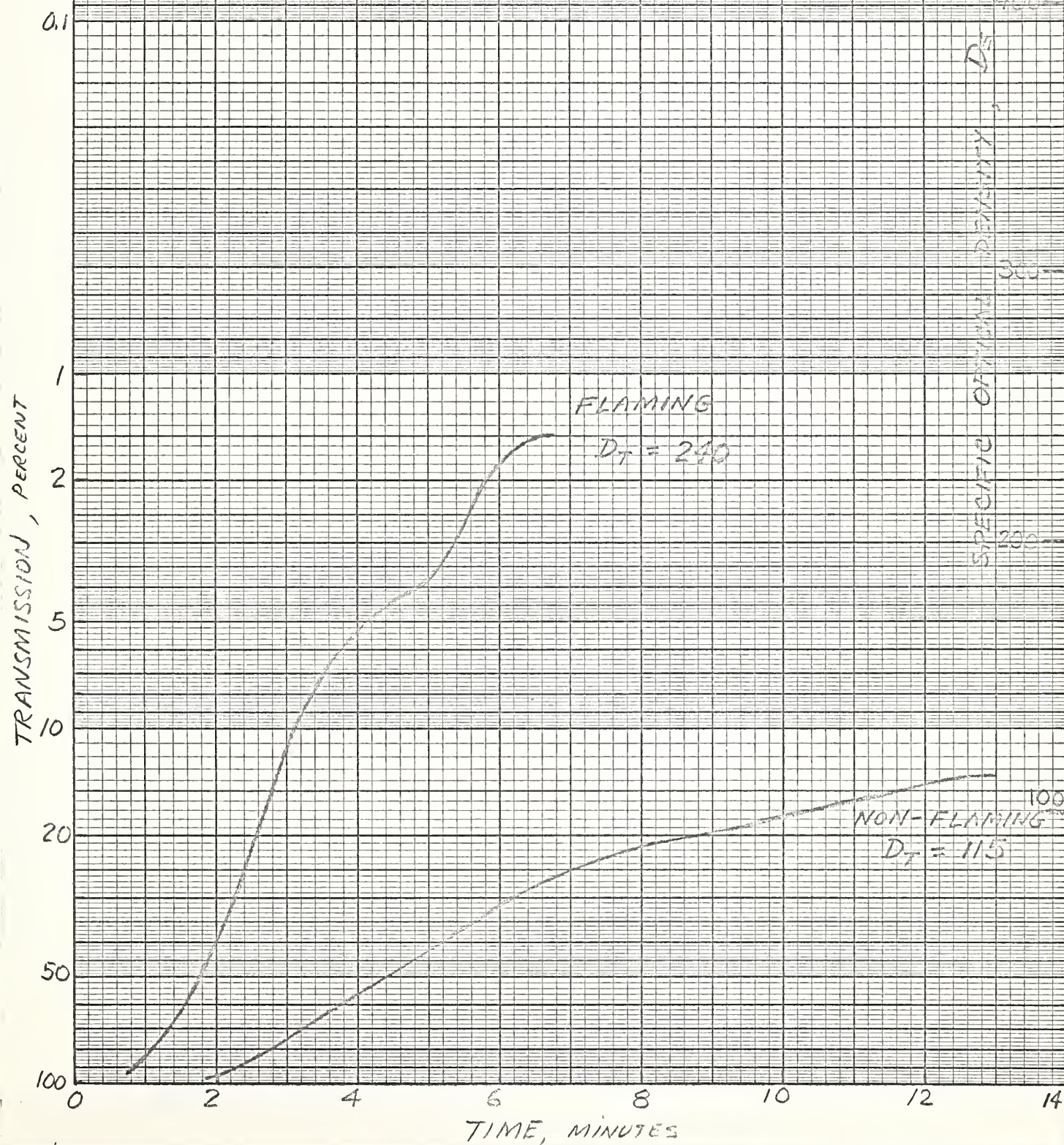
12

14

TIME, MINUTES

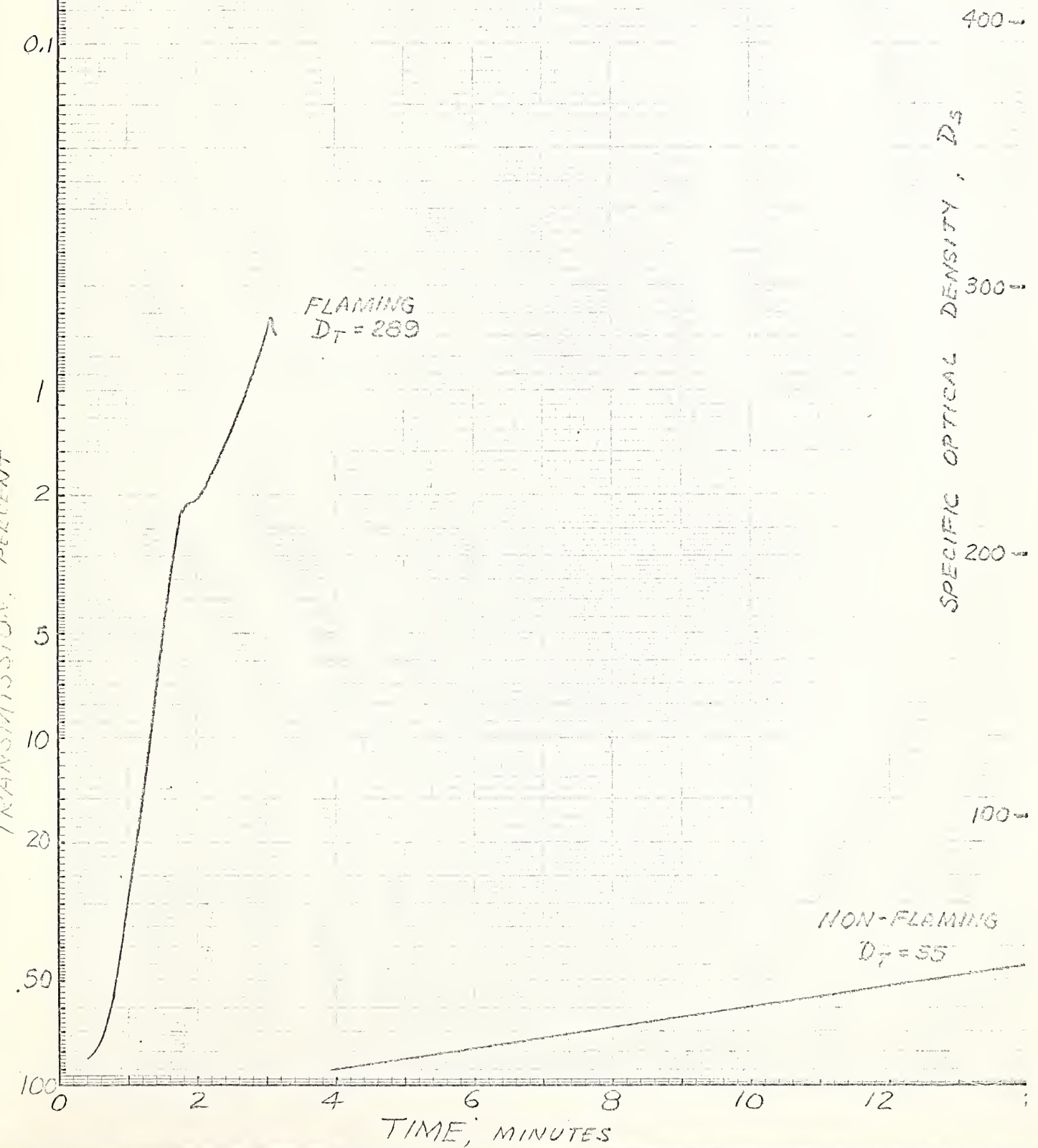


SMOKE PRODUCTION
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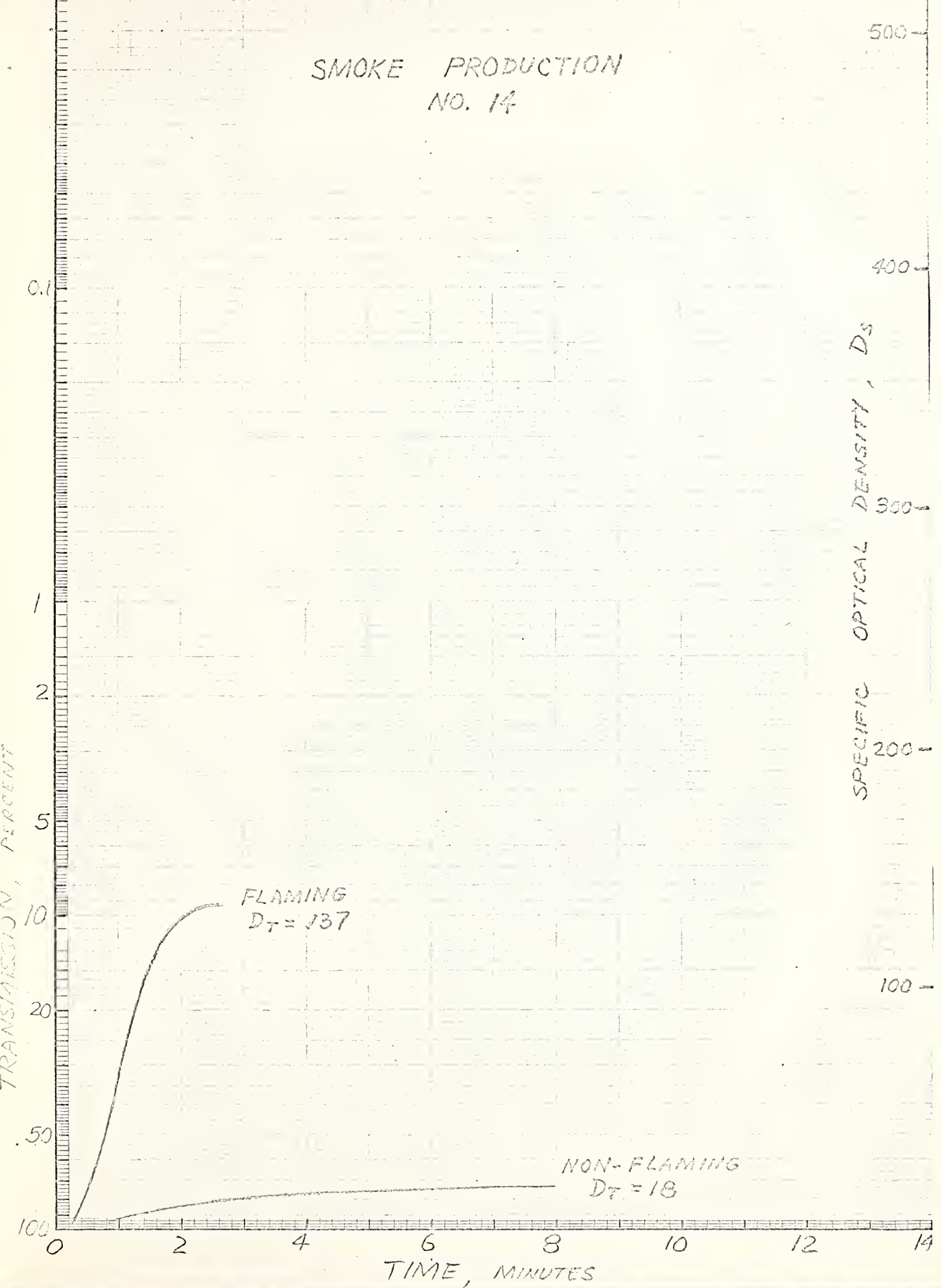


SMOKE PRODUCTION

No. 13



SMOKE PRODUCTION NO. 14



SMOKE PRODUCTION
NO. 15

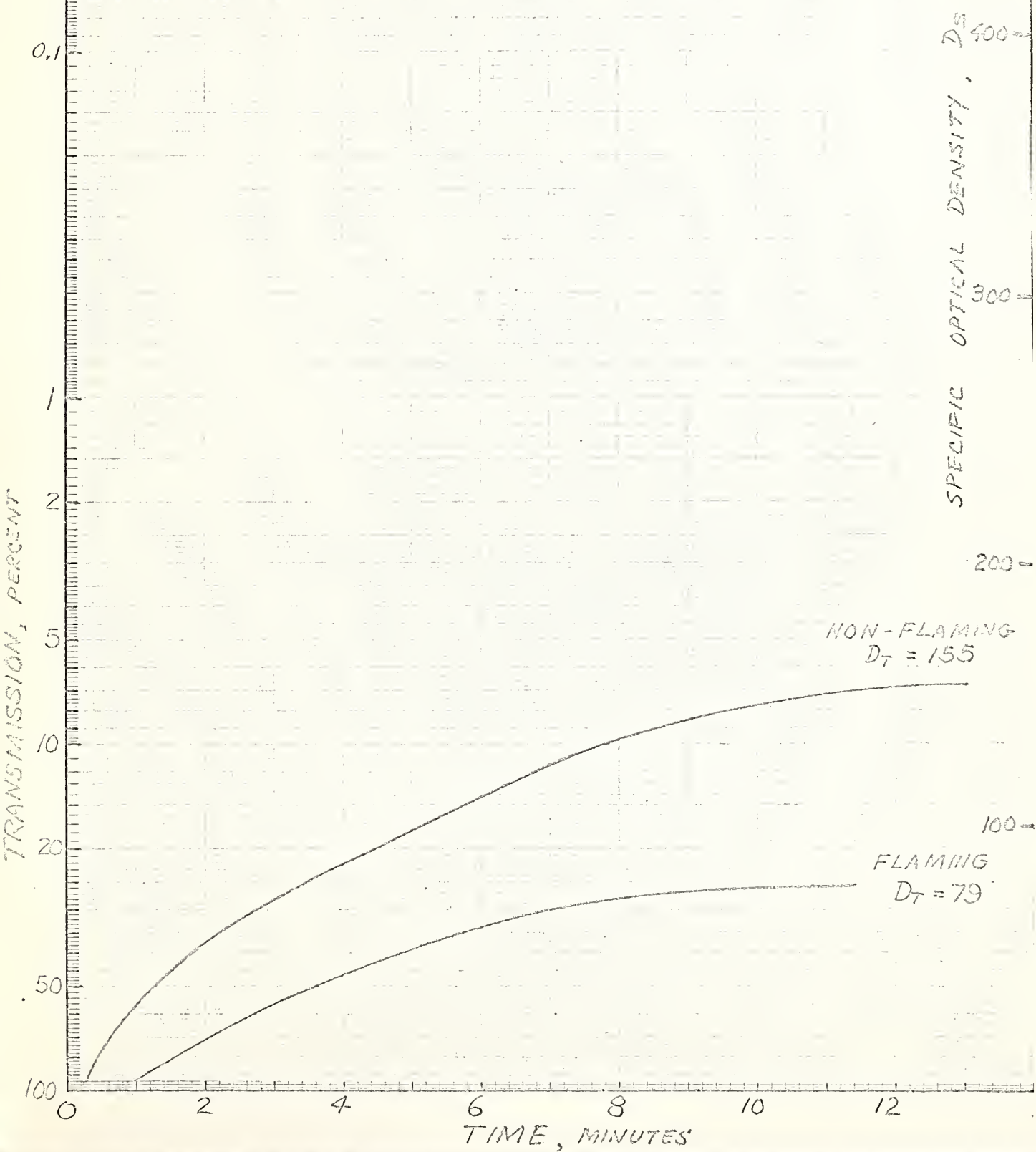


FIG. 16 SPECIFIC OPTICAL DENSITY VS. GEOMETRICAL FACTOR
FOR FIVE SELECTED LIGHT TRANSMISSION VALUES

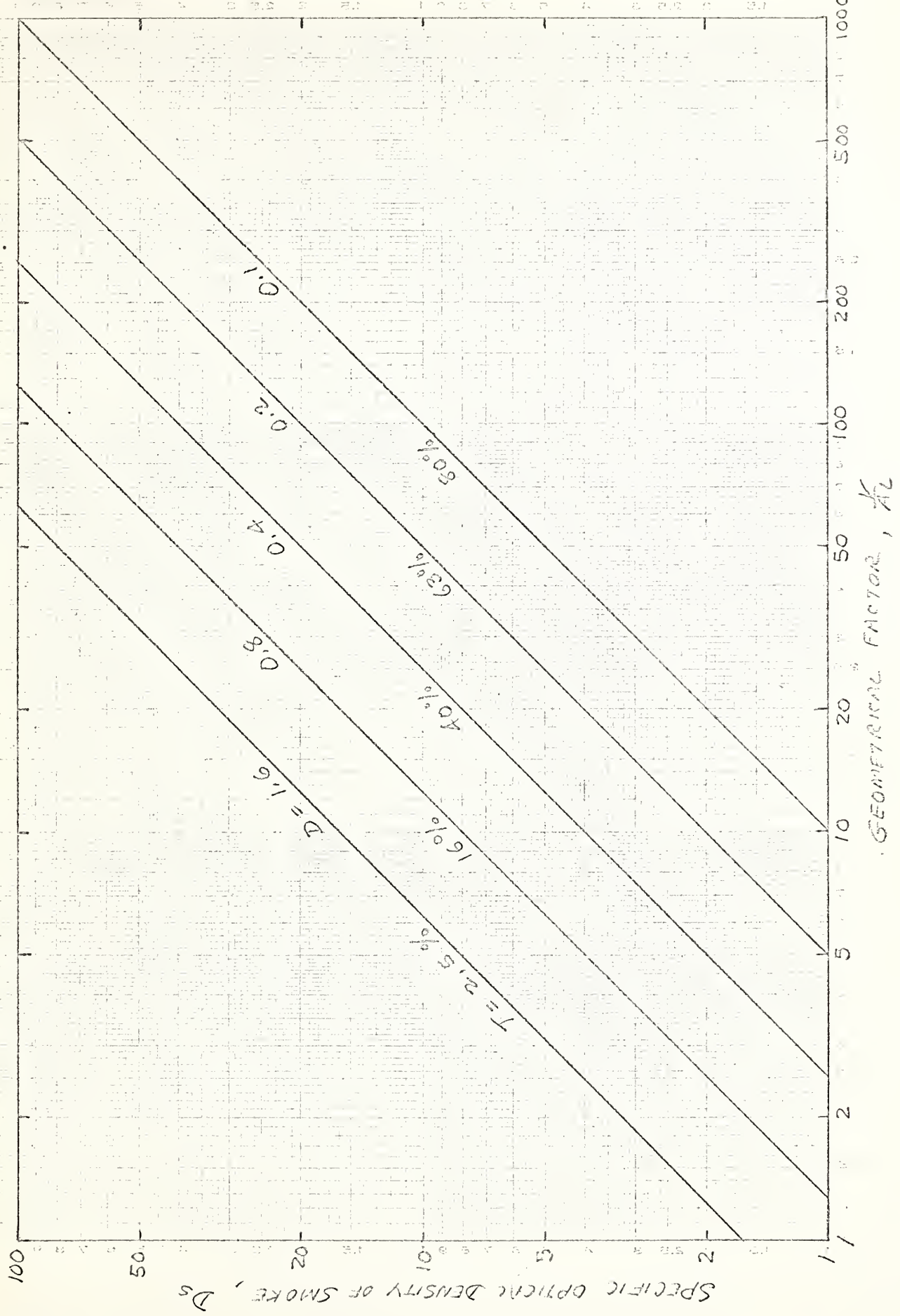


FIG. 17 GAS CONCENTRATION IN 10,000 FT³ CABIN BASED ON INDICATED CONCENTRATION IN SMOKE TEST CHAMBER

